Mon. Not. R. Astron. Soc. **351,** L78–L82 (2004) doi:10.1111/j.1365-2966.2004.08053.x

Prediction on the very early afterglow of X-ray flashes

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Accepted 2004 May 21. Received 2004 May 21; in original form 2004 March 25

ABSTRACT

In the past two years, tremendous progress in understanding X-ray flashes has been made. Now it is widely believed that X-ray flashes and gamma-ray bursts are intrinsically the same, and that their very different peak energy and flux may be merely due to our different viewing angles to them. Here we analytically calculate the very early afterglow of X-ray flashes, i.e. the reverse shock emission powered by the outflows interacting with the interstellar medium. Assuming $z \sim 0.3$, we have shown that typically the R-band flux of reverse shock emission can be bright to ∼16–17th magnitude (the actual values are model-dependent and sensitive to the initial Lorentz factor of the viewed ejecta). That emission is bright enough to be detected by the telescope on work today such as Robotic Optical Transient Search Experiment (ROTSE-III) or the upcoming Ultraviolet and Optical Telescope (UVOT) carried by the *Swift* satellite, planned for launch in late 2004.

Key words: radiation mechanisms: non-thermal – gamma-rays: bursts – X-rays: general.

1 INTRODUCTION

X-ray flashes (XRFs) have received increasing attention in the past several years (e.g. Heise et al. 2002; Kippen et al. 2002). In many respects, XRFs are similar to 'classical' gamma-ray bursts (GRBs):

(1) their sky distribution is nearly isotropic;
(2) the redshift $z = 0.251$ of XRF 020903 (Soderberg et al. 2004) and afterglows of XRF 020903 and XRF 030723 have been detected (Soderberg et al. 2002; Prigozhin et al. 2003), which suggests that XRFs are also cosmic events;
(3) they have T_{90} durations ranging from 20 to 200 s;
(4) their spectrum can also be fitted by the band spectrum (Kippen et al. 2002);
(5) they have temporal structure very similar to the X-ray counterparts of GRBs (Heise et al. 2002).

However, their spectral peak energies $E_{\rm peak,obs} \sim 10$ keV are much lower than those of GRBs (∼300 keV). These similarities lead to the suggestion that XRFs are the extension of GRBs and X-ray-rich GRBs to an even softer regime (Kippen et al. 2002; Lamb, Donaghy & Graziani 2004).

Now there are several models proposed to account for XRFs, i.e. the off-beam uniform jet model (e.g. Ioka & Nakamura 2001; Yamazaki, Ioka & Nakamura 2002); the wide opening angle uniform jet model (e.g. Lamb et al. 2004); the Gaussian jet model (e.g. Zhang & Mészáros 2002a; Lloyd-Ronning, Dai & Zhang 2004; Zhang et al. 2004a); the power-law jet model (e.g. Mészáros, Rees & Wijers 1998; Jin & Wei 2004); the two-component jet model (e.g. Zhang, Woosley & Heger 2004b; Huang et al. 2004) and the cannonball model (Dado, Dar & De Rujula 2003).

In this Letter, instead of taking a further investigation of these models, we turn to calculate the possible accompanying very early afterglows. We are mostly inspired in this by the upcoming *Swift* satellite,[1] which carries three main telescopes: the Burst Alert Telescope (BAT), the X-ray Telescope (XRT), and the Ultraviolet and Optical Telescope (UVOT). The energy range of BAT is 15–150 keV. Considering its high sensitivity, XRFs with peak energies that are not too much lower can be detected as well as GRBs. BAT will observe and locate hundreds of bursts per year to better than 4 arcmin accuracy. Using this prompt burst location information, *Swift* can slew quickly to point the on-board XRT and UVOT at the burst for continued afterglow studies. The spacecraft's 20–70 s time-to-target means that about ∼100 GRBs+XRFs per year (about 1/3 of the total) will be observed by the narrow field instruments during the gamma-ray emission. The UVOT is sensitive to magnitude 24 in a 1000-s exposure. (For a linear increase of sensitivity with exposure time, that means a sensitivity of magnitude 19 in a 10-s exposure.) Then, the very early afterglow of XRFs can be detected directly, though it may be dimmer than that of GRBs.[2]

2 THE VERY EARLY AFTERGLOW OF GRBs

In the standard fireball model for gamma-ray bursts, the very early afterglow of GRBs powered by the ejecta interacting with the

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[1] http://swift.gsfc.nasa.gov/science/instruments
[2] By now, there is only one upper limit ($m_{\rm R} > 19$) at a time ∼50 s after the main burst of XRF 030723 has been reported (Smith et al. 2003).

interstellar medium (ISM) or stellar wind has been discussed in great detail (e.g. Sari & Piran 1999; Mészáros & Rees 1999; Kobayashi 2000; Li et al. 2003; Nakar & Piran 2004; Wu et al. 2003; Kobayashi & Zhang 2003a). Recently, the reverse shock (RS) emission powered by magnetized outflows – medium interaction has been discussed by Fan, Wei & Wang (2004a) and Zhang & Kobayashi (2004) independently. So far there are three very early afterglows that have been detected (see Sari & Piran 1999; Kobayashi & Zhang 2003b; Wei 2003, and the references therein). With the launching of *Swift*, that number may be increased greatly.

Modelling the very early afterglow can be used to constrain some poorly known physical parameters, such as the initial Lorentz factor of the outflow, ϵ_B (the fraction of the internal energy converted into magnetic energy) and so on (e.g. Wang, Dai & Lu 2000). Interestingly, it is found that the RS emission regions of GRB 990123 and GRB 021211 are likely to be magnetized (Fan et al. 2002; Zhang, Kobayashi & Mészáros 2003; Kumar & Panaitescu 2003).

3 THE VERY EARLY AFTERGLOW OF XRFs

One of obstacles we encountered in the current work is the poorly known angular distribution of the initial Lorentz factor of these jets except the off-beam one. Kumar & Granot (2003) have performed a numerical investigation on the hydrodynamical evolution of a Gaussian jet by assuming $\eta(\theta)$ is also Gaussian distribution. However, if the viewed Lorentz factor $\eta(\theta_v)$ is significantly lower than 100 and XRFs are powered by internal shocks, the observed spectrum should be thermal, which is inconsistent with the current observation. In their Monte Carlo simulation, Zhang et al. (2004a) have taken $\eta(\theta)$ as a free function but found that a flat (or at most slightly variable) angular distribution of Lorentz factor is indeed required to interpret the current observations, particularly the empirical relationship[3] $E_{\rm peak} \propto E_{\rm iso}^{1/2}$. Therefore, and partly for convenience, we assume $\eta(\theta_v) = \text{const} \sim 150$. For the off-beam jet model, XRFs are intrinsically the GRBs. As usual, we take $\eta = 300$.

In this work, we assume $\eta(\theta_v) = \text{constant} \sim 150$ for all on-beam jets (i.e. the Gaussian jet, the power-law jet, the wide opening jet and the two-component jet). In contrast to the off-beam case, for these four types of jets there are relativistically moving materials beaming towards the observer. As long as the Lorentz factor is large enough, within the $1/\gamma$ cone the jet structure effect is not significant, and all these four models would give a rather similar early afterglow light curves. Their differences would only appear in much later epochs when the jet-structure effect becomes prominent. So, for illustrative purposes, in this Letter only the possible RS emission powered by the Gaussian jet and the off-axis jet interacting with ISM have been calculated.

3.1 The RS emission of the off-beam jet

For a uniform jet, if the line of sight is slightly beyond the cone, i.e. $\Delta\theta \equiv \theta_v - \theta_{\rm jet} > 0$ ($\theta_{\rm jet}$ is the opening angle of the jet, θ_v is our viewing angle to the jet), and the observed peak energy decreases as

$$\nu_{\rm off} = a\nu_{\rm on}, \tag{1}$$

where $\nu_{\rm on/off}$ are the observed frequency on/off-axis respectively, $a \approx [1+\gamma^2(\Delta\theta)^2]^{-1}$ (e.g. Granot et al. 2002). On the contrary, the observed duration is increased by a factor of a^{-1}. Then a 'classical' GRB will be detected as a long-lasting XRF (e.g. Ioka & Nakamura 2001; Yamazaki et al. 2002). By assuming an accompanying supernova, it is claimed that the off-beam jet model can fit the later afterglow of XRF 030723 quite well (Fynbo et al. 2004).

The afterglow of the off-beam jet has been numerically calculated by many authors, and an empirical formula has been proposed to estimate the observed flux (e.g. Granot et al. 2002; Jin & Wei 2004):

$$F_{\nu_{\rm off}}(\Delta\theta, t_{\rm obs}) \approx \frac{a^3}{2} F_{\nu_{\rm on}}(0, t), \tag{2}$$

where $dt_{\rm obs} = dt/a$. Different from the long-lasting forward shock (FS), the RS disappears after it crosses the ejecta. The crossing time is estimated by $t_\times = \max\{t_{\rm dec}, T_{\rm dur}\}$, where two time-scales are involved.

(i) The deceleration time $t_{\rm dec}$ can be calculated as follows. The outflow is decelerated significantly at the deceleration radius (Rees & Mészáros 1992)

$$R_{\rm dec} \approx 5.6 \times 10^{16}\text{cm}\ E_{\rm iso,53}^{1/3} n_{1,0}^{-1/3} \eta_{2.5}^{-2/3}, \tag{3}$$

where $E_{\rm iso} \sim 10^{53}$ erg is the typical isotropic energy of the GRB outflow, $n_1 \sim 1$ is the number density of the ISM and $\eta \sim 300$ is the initial Lorentz factor of the outflow at the end of $\gamma-$ray emission phase. Throughout this Letter, we adopt the convention $Q_x = Q/10^x$ for expressing the physical parameters, using cgs units. At $R_{\rm dec}$, the Lorentz factor of the outflow drops to $\gamma_{\rm dec} \simeq \eta/2$. The corresponding time-scale is

$$t_{\rm dec} \approx R_{\rm dec}/2\gamma_{\rm dec}^2 c = 40\,\text{s}\ R_{\rm dec,16.75}\gamma_{\rm dec,2.18}^{-2}. \tag{4}$$

(ii) $T_{\rm dur}$, the local duration of the GRB corresponding to the XRF, can be estimated as follows. In the off-beam jet model of XRFs, the observed duration of XRF is $\sim(1+z)a_0^{-1}T_{\rm dur}$, where $a_0 \equiv [1+\eta^2(\Delta\theta)^2]^{-1}$. Here we take $a_0 \simeq 0.03$ – for much smaller a_0, the observed luminosity ($L \propto a_0^4$) is too dim to be detected; for much larger a_0, the observed peak energy ($\propto a_0$) is in the hard X-ray energy, i.e. what we observe is an X-ray rich burst rather than XRF. One potential problem of the off-beam model is that, in principle, the typical duration of XRFs should be ten times of that of typical GRBs, which has not been supported by the present observations (the observed duration of the XRFs ranges from 20 s to 200 s). Here we take $T_{\rm dur} \sim 10$ s, which matches that of the 'classical' long GRBs [$\sim$20 s$/(1+z')$, $z' \sim 1$ is the typical redshift of GRBs].

For $t_{\rm dec} > T_{\rm dur}$, the shell is thin, otherwise the shell is thick (Sari & Piran 1999; Kobayashi 2000). For the parameters taken here, we have $t_{\rm dec} > T_{\rm dur}$, so the shell is thin (if the shell is thick, the following discussion is invalid and we refer the reader to see Section 3.2 for detailed treatment). Consequently, $t_\times = t_{\rm dec}$, $\gamma_\times = \gamma_{\rm dec}$ and $R_\times = R_{\rm dec}$ ($\gamma_\times$ is the bulk Lorentz factor of the outflow at $t_\times$, $R_\times$ is the corresponding radius).

The Lorentz factor of the shocked outflow relative to the initial one is

$$\gamma_{34,\times} \approx (\eta/\gamma_\times + \gamma_\times/\eta)/2 = 1.25, \tag{5}$$

which suggests that the RS is only mildly relativistic.

At $R_\times$, all the electrons contained in the outflow have been heated by the RS and distribute as $dn/d\gamma_e \propto \gamma_e^{-p}$ for $\gamma_e > \gamma_{\rm e,m}$ (throughout this Letter we take $p = 2.2$), where the 'minimal' thermal Lorentz factor, $\gamma_{\rm e,m}$, can be estimated by

$$\gamma_{\rm e,m} = \frac{m_p}{m_e}\frac{p-2}{p-1}\epsilon_e(\gamma_{34,\times} - 1) = 23F, \tag{6}$$

[3] Its validity for GRBs and XRFs has been verified by many authors (e.g. Lloyd-Ronning, Petrosian & Mallozzi 2000; Amati et al. 2002; Zhang & Mészáros 2002b; Wei & Gao 2003; Lamb et al. 2004; Liang, Dai & Wu 2004).

where $F \equiv \epsilon_{e,-0.5}(\gamma_{34,\times} - 1)/0.25$, ϵ_e is the fraction of thermal energy obtained by the electrons, $m_p(m_e)$ are the rest mass of proton (electron) respectively. The typical synchrotron radiation frequency can be estimated by

$$\nu_{m,\times} = \frac{\gamma_{e,m}^2 \gamma_\times eB}{2(1+z)\pi m_e c} = \frac{4.0\times 10^{12}}{1+z}\,\mathrm{Hz} F^2 \epsilon_{B,-1}^{1/2} n_{1,0}^{1/2} \gamma_{\times,2.18}^2, \quad (7)$$

where $B \approx 0.12$ G $n_{1,0}^{1/2}\epsilon_{B,-1}^{1/2}\gamma_\times$ (e.g. Fan et al. 2002) is the magnetic strength generated in the RS. Here we take $\epsilon_B \sim 0.1$ rather than 0.01 since the ejecta is likely to be magnetized (e.g. Fan et al. 2002; Zhang et al. 2003). The cooling Lorentz factor of the shocked electrons is (Sari, Piran & Narayan 1998, hereafter SPN) $\gamma_{c,\times} \approx 6\pi\, m_e c/(\sigma_T \gamma_\times B^2 t_\times) \approx 360$ (assuming the involved $Q_x = 1$), where σ_T is the Thompson cross-section. Correspondingly, the cooling frequency is $\nu_{c,\times} = (\gamma_{c,\times}/\gamma_{e,m})^2 \nu_m \approx 10^{15}/(1+z)$ Hz. For $z = 0.3$ (as is generally suggested for XRFs), $\nu_{c,\times}$ is larger than the observer frequency $\nu_{R,obs} = 4.6\times 10^{14}$ Hz. Following Wu et al. (2003, see their appendix A1 for details), the synchrotron self-absorption frequency of the compressed outflow is $\nu_{a,\times} \approx 3.6\times 10^{12}/(1+z)$ Hz (assuming the involved $Q_x = 1$). So the synchrotron self-absorption effect cannot significantly change the R-band spectrum, a fact of interest.

At $R_\times$, the on-beam peak flux can be estimated by $F_{\nu,\max(\mathrm{on})} \approx (1+z)N_e m_e c^2 \sigma_T \gamma_\times B/12\pi e D_L^2 \approx 92.3[(1+z)/1.3]$ Jy $E_{\mathrm{iso},53}\eta_{2.5}^{-1}\gamma_{\times,2.18}^2 n_{1,0}^{1/2}\epsilon_{B,-1}^{1/2} D_{L,27.7}^{-2}$ (SPN), where $N_e = E_{\mathrm{iso}}/\eta m_p c^2$ is the total number of electrons contained in the outflow, D_L is the luminosity distance (we assume $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$, $\Omega_\wedge = 0.73$). With equation (2), the off-axis observed energy flux can be estimated by (SPN)

$$F_{\nu_{R,obs}(\mathrm{off})} \approx \frac{a_\times^3}{2} F_{\nu,\max(\mathrm{on})}\left(\frac{\nu_{R,obs}}{a_\times \nu_{m,\times}}\right)^{-(p-1)/2} = 0.8\,\mathrm{mJy}\,(9a_\times)^{\frac{(p+5)}{2}} E_{\mathrm{iso},53}\eta_{2.5}^{-1}\gamma_{\times,2.18}^{p+1} \times F^{p-1}\epsilon_{B,-1}^{\frac{p+1}{4}} n_{1,0}^{\frac{p+1}{4}}\left(\frac{1+z}{1.3}\right)^{\frac{3-p}{2}} D_{L,27.7}^{-2}, \quad (8)$$

where $a_\times = [1+(\gamma_\times\Delta\theta)^2]^{-1}$. If we take $a_0 = 0.03$, i.e. $\eta\,\Delta\theta = 5.7$ (see the reasons mentioned in the paragraph below equation 4), we have $a_\times = 1/9$, i.e. $\gamma_\times\Delta\theta = 2.8$. The observed crossing time $t_{\times,obs} \sim t_\times/a_\times \approx 360(1+z)$ s. In the R band, the magnitude $m_R \approx 17$, which is bright enough to be detected by the telescopes on work today, or the upcoming UVOT.

Here, we briefly discuss the observed very early afterglow light curve. In the case of a thin shell, the on-axis light curve is well approximated by (for $\nu_m < \nu < \nu_{c,\times}$, i.e. the slow cooling case)

$$F_{\nu(\mathrm{on})} \propto \begin{cases} t^{2p}, & \text{for } t < t_\times \sim t_{\mathrm{dec}}, \\ t^{-(11p+3)/14}, & \text{for } t > t_\times \sim t_{\mathrm{dec}}. \end{cases} \quad (9)$$

The light curve for $t > t_\times$ is presented in Mészáros & Rees (1999); we assume the comoving magnetic field contained in the shocked outflow is freezing and taking $g = 3$, since for the parameters adopted in this Letter the FS emission is in fast cooling. The light curve for $t < t_\times$ adopted here is slightly different from that of Kobayashi (2000) and Fan et al. (2002). Below we derive it in some detail. For the Newtonian RS, the bulk Lorentz factor of the ejecta $\gamma \sim \eta$, $\gamma_{34} - 1 \propto (n_4/n_1)^{-1} \propto R^2$ (Sari & Piran 1995), where n_4 is the comoving number density of the outflow, $R \simeq 2\eta^2 ct$ is the radius of the outflow. Therefore $\gamma_{34} - 1 \propto t^2$, and substituting it into equation (7) we have $\nu_m \propto t^4$. On the other hand, $\beta_{34} \propto t$,

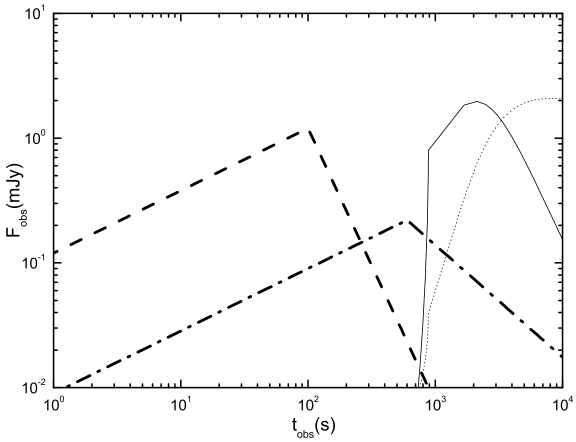

Figure 1. The sample very early R-band ($\nu_{R,obs} = 4.6\times 10^{14}$ Hz) light curves powered by the outflows interacting with the ISM. The solid/dotted lines represent the RS/FS emission as a function of observer time of the off-beam uniform jet; the thick dashed/dash–dotted lines represent the RSFS emission as a function of time of the Gaussian jet. The parameters for plotting the solid/dotted lines are: $T_{\mathrm{dur}} = 10$ s, $\Delta\theta = 0.019$ rad, $\eta = 300$, $E_{\mathrm{iso}} = 10^{53}$ erg, $z = 0.3$, $p = 2.2$, $\epsilon_e = \epsilon_{e,f} = 0.3$, $\epsilon_B = 0.1$, $\epsilon_{B,f} = 0.01$. For plotting the thick-dashed/dash–dotted lines, the parameters are the same except $T_{90} = 100$ s, $\eta(\theta_v) = 150$, $E_{\mathrm{iso}(\theta_v)} = 10^{50}$ erg.

which results in $N_e' \propto t^2$, where N_e' is the number of shocked electrons. Substituting these relations into the expression of $F_{\nu,\max(\mathrm{on})}$, we have $F_{\nu,\max(\mathrm{on})} \propto t^2$. Therefore the observed R-band light curve $F_{\nu_{R,obs(on)}} \propto t^2 (t^{-4})^{-(p-1)/2} \propto t^{2p}$.

Assuming $\gamma = \eta(1 - t/2t_\times)$ for $t < t_\times$, we have

$$t_{\mathrm{obs}} \approx \left[\frac{1}{a_0} - \frac{1}{2}\left(\frac{1}{a_0} - 1\right)\frac{t}{t_\times}\right] t;$$

for $t > t_\times$, $\gamma = \eta\,(t/t_\times)^{-3/7}/2$, we have

$$t_{\mathrm{obs}} \approx \frac{5(a_0 - 1)}{4a_0} t_\times + \left[1 + \frac{7}{4}\left(\frac{1-a_0}{a_0}\right)\left(\frac{t_\times}{t}\right)^{6/7}\right] t.$$

With these relations (including equations 2 and 9), we obtain one sample light curve of the RS emission powered by the off-beam uniform jet–ISM interaction, which has been presented in Fig. 1 (the solid line). Naturally, for $t_{\mathrm{obs}} < t_{\mathrm{obs},\times}$, the increasing of the light curve is more rapidly than t_{obs}^{2p}. For $t_{\mathrm{obs}} > t_{\mathrm{obs},\times}$, as long as $\gamma\,\Delta\theta$ is not much smaller than 1, the factor $a^{(p+5)/2}$ increases rapidly. Therefore, at early time, the optical emission increases, rather than decreases with time. At much later time, $\gamma\,\Delta\theta \to 1$, the factor $a^{(p+5)/2}$ increases only slightly. So the light curve of RS emission drops as $\propto t_{\mathrm{obs}}^{-2}$ (Fig. 1, the thin solid line).

Taking $\epsilon_{B,f} = 0.01$, $\epsilon_{e,f} = \epsilon_e$ (the subscript f represents the forward shock), we have the following result: at $t_{\times,obs}$, $F_{\nu_{R,obs(off)},f} \approx 0.04$ mJy. For $t > t_{\times,obs}$, $F_{\nu_{R,obs(on),f}} \propto t^{-1/3}$ (e.g. SPN). With equation (2) and

$$t_{\mathrm{obs}} \approx \frac{5(a_0 - 1)}{4a_0} t_\times + \left[1 + \frac{7}{4}\left(\frac{1-a_0}{a_0}\right)\left(\frac{t_\times}{t}\right)^{6/7}\right] t,$$

the sample early light curve of the FS emission has been presented in Fig. 1 (the dotted line).

3.2 The RS emission of Gaussian jet

For a Gaussian jet, the observed isotropic energy $E_{\mathrm{iso}(\theta_v)} = E_{\mathrm{iso}(\theta_v=0)}\exp(-\theta_v^2/2\theta_0^2)$. Typically, the observed peak energy of

XRF is about 0.03 times that of GRBs and $E_{\rm iso(\theta_v)} \sim 10^{-3} E_{\rm iso(\theta_v=0)}$. The corresponding viewing angle is $\theta_{\rm v} \approx 3.7\theta_0$. Taking $\eta(\theta_{\rm v}) = 150$, equation (3) gives $R_{\rm dec} \sim 8.8 \times 10^{15}$ cm. Correspondingly, $t_{\rm dec} \sim 25$ s, which is much shorter than the typical duration of the XRFs $T_{90} \sim 100$ s, i.e. *the shell is thick*. So, locally $t_\times \approx T_{90}/(1+z)$, with which $R_\times$ and $\gamma_\times$ can be calculated self-consistently.

At $R_\times$, the energy conservation of the system, i.e. the shocked ISM and the shocked viewing outflow, gives

$$\gamma_\times \gamma_{34,\times} M_{\rm ej} + \gamma_\times^2 M_{\rm sw} \approx \eta(\theta_{\rm v}) M_{\rm ej}, \tag{10}$$

where $M_{\rm ej}(M_{\rm sw})$ is the mass of the viewed ejecta (the swept ISM). In the thick shell case, the RS is mild-relativistic and $\gamma_{34,\times} \approx \eta(\theta_{\rm v})/2\gamma_\times$. Now equation (10) reduces to $\gamma_\times^2 M_{\rm sw} \approx \eta(\theta_{\rm v})\, M_{\rm ej}/2$. Considering that $M_{\rm sw} = (4\pi/3) R_\times^3 n_1 m_{\rm p}$ and $T_{90}/(1+z) \approx R_\times/2\gamma_\times^2 c$, we have

$$R_\times \approx 1.4 \times 10^{16}\ {\rm cm}\ E_{\rm iso(\theta_v),50}^{1/4} n_{1,0}^{-1/4} T_{90,2}^{1/4} \left(\frac{1.3}{1+z}\right)^{1/4}, \tag{11}$$

$$\gamma_\times \approx 55 E_{\rm iso(\theta_v),50}^{1/8} n_{1,0}^{-1/8} T_{90,2}^{-3/8} \left(\frac{1+z}{1.3}\right)^{3/8}. \tag{12}$$

Now $\gamma_{34,\times} \approx 1.55$, which is mildly relativistic. So the assumption made before is reasonable. Similar to Section 3.1, the typical frequency of RS emission can be estimated by

$$\nu_{\rm m,\times} = \frac{3.8 \times 10^{12}}{1+z}\ {\rm Hz}\ F_1^2 n_{1,0}^{1/2} \epsilon_{\rm B,-1}^{1/2} \gamma_{\times,1.74}^2, \tag{13}$$

where $F_1 \equiv \epsilon_{\rm e,-0.5}(\gamma_{34,\times} - 1)/0.55$. Similarly, taking $Q_{\rm x} = 1$ and $z = 0.3$ we have $\nu_{\rm c,\times} \sim 2.9 \times 10^{16}$ Hz. Following Wu et al. (2003), the synchrotron self-absorption frequency is $\nu_{\rm a,\times} \sim 4.5 \times 10^{10}$ Hz. Therefore both of them can not affect the R band spectrum significantly. The peak flux of RS emission can be estimated by $F_{\nu,\max} \approx 28\ {\rm mJy}[(1+z)/1.3] E_{\rm iso(\theta_v)}, 50\eta_{2.18}^{-1} \gamma_{\times,1.74}^2 n_{1,0}^{1/2} \epsilon_{\rm B,-1}^{1/2} D_{\rm L,27.7}^{-2}$. Then the observed peak energy flux can be estimated by (SPN)

$$\begin{aligned} F_{\nu_{\rm R,obs}} &\approx F_{\nu,\max} \left(\frac{\nu_{\rm R,obs}}{\nu_{\rm m,\times}}\right)^{-(p-1)/2} \\ &= 1.2\ {\rm mJy}\ E_{\rm iso(\theta_v),50} \eta_{2.18}^{-1} \gamma_{\times,1.74}^{p+1} F_1^{\,p-1} \epsilon_{\rm B,-1}^{\frac{p+1}{4}} n_{1,0}^{\frac{p+1}{4}} \\ &\quad \left(\frac{1+z}{1.3}\right)^{(3-p)/2} D_{\rm L,27.7}^{-2}, \end{aligned} \tag{14}$$

the magnitude $m_{\rm R} \approx 16$, which is also bright enough to be detected by the upcoming UVOT or the telescopes working today, as long as the response to the XRF is fast enough.

In the case of a thick shell, the very early light curve of a standard fireball takes the form (for the parameters adopted in this Letter, the reverse/FS emission is all in slow cooling, for $t > t_\times$):

$$F_{\nu_{\rm R,obs}} \propto \begin{cases} t^{1/2}, & \text{for } t < t_\times \sim T_{90}/(1+z), \\ t^{-3(5p+1)/16}, & \text{for } t > t_\times \sim T_{90}/(1+z). \end{cases} \tag{15}$$

Thanks to the beaming effect, these scaling laws may be applied to the current work as well. Here we simply take equation (15) to plot the sample very early light curve powered by a Gaussian jet–ISM interaction (see Fig. 1, the thick-dashed line). The corresponding light curve of the FS emission (see Fig. 1, the thick dash–dotted line) is plotted as follows. Following SPN, at $t_{\times,\rm obs} = (1+z)t_\times$, $F_{\nu_{\rm R,obs},\rm f} \approx 0.09$ mJy. For $t < t_0$, $F_{\nu_{\rm R,obs},\rm f} \propto t^{1/2}$ [where t_0 is determined by $\nu_{\rm m,f}(t_0) = (1+z)\nu_{\rm R,obs}$]; For $t > t_0$, $F_{\nu_{\rm R,obs},\rm f} \propto t^{-0.9}$.

As shown in Fig. 1, in many respects, e.g. the peak time and the temporal behaviour, the current light curve is very different from that powered by the off-beam jet–ISM interaction, which may help us to distinguish them. For example, the FS peak emission of the off-beam jet is much brighter than that of Gaussian jet, which is mainly due to the following reasons. In the off-beam jet model, we take $\Delta\theta = 0.019$ rad. At several thousand seconds after the main burst, the ejecta has been decelerated significantly ($\gamma < 50$), as a result, the beaming effect is not important. So the viewed isotropic energy of the 'off-beam' ejecta is nearly $E_{\rm iso}$, which is much larger than that of the Gaussian jet model ($\sim E_{\rm iso(\theta_v)}$) in which $\theta_{\rm v} \simeq 0.2$ rad (Zhang et al. 2004), the emission powered by the central energetic ejecta can not be observed at early times as long as $\gamma \gg 5$.

4 DISCUSSION AND CONCLUSION

In the past several years, XRFs have received more and more attention, but their nature remains unknown. Considering the similarity between XRFs and GRBs as regards duration, temporal structure, spectrum and so on, these bursts may be the same phenomenon. The different peak energy as well as the peak energy flux may be merely due to our different viewing angles to them. This viewpoint has been supported by the recent detection of two afterglows and one redshift of XRFs. However, more than six models have been proposed to explain the XRFs. Some of them (for example, the Gaussian jet model, the off-beam uniform jet model) work well in explaining the current observation. Perhaps only the detailed multiwavelength afterglows modelling (including the very early afterglow discussed in this Letter) can provide us with a reliable identification on them.

With two current leading models, in this Letter, the very early RS emission of XRFs has been analytically investigated. As XRFs are much dimmer than GRBs, the predicted very early R-band afterglow of XRFs is dimmer than those of GRBs. But some of them, if not all, are still bright enough to be detected by ROTSE-III in work today or by the upcoming *Swift* mission. The actual results are model-dependent, which may in turn provide us a chance to see which one is better, if the very early afterglow of XRFs has been really detected. One thing should be emphasized here is that the predicted R-band flux is sensitive to the initial Lorentz factor, i.e. $F_{\nu_{\rm R,obs}} \propto \eta(\theta_{\rm v})^{-1} \gamma_\times^{p+1} (\gamma_{34,\times} - 1)^{p-1}$. So, if $\eta(\theta_{\rm v}) \sim$ tens rather than 150 taken in this Letter, the resulting very early optical emission will be much dimmer.

As realized by more and more 'GRB people', modelling the very early afterglow of GRBs can impose some stringent constraint on the fundamental physical parameters of the outflow such as the initial Lorentz factor of the ejecta (e.g. Sari & Piran 1999; Wang et al. 2000), or help to see whether the outflows are magnetized or not (e.g. Fan et al. 2002; Zhang et al. 2003; Kumar & Panaitescu 2003; Fan et al. 2004b; Zhang & Kobayashi 2004). In addition, the RS emission powered by the ejecta–stellar wind interaction is very different from that powered by the ejecta–ISM interaction (e.g. Wu et al. 2003; Kobayashi & Zhang 2003a; Fan et al. 2004b). Therefore the very early afterglow observation can provide us with an independent chance to determine the environment where the 'classical' GRB was born in. In principle, interstellar wind environment may be common, and the predicted very early R-band emission is very strong ($m_{\rm R} \sim 9$ or even brighter). So far there are only three very early afterglow having been reported. All of them can be well fitted by the ejecta–ISM interaction model (e.g. Sari & Piran 1999; Kobayashi & Zhang 2003b; Wei 2003). Therefore, in this Letter only the ejecta–ISM interaction case has been investigated. Fortunately, it is straightforward to extend our treatment to the wind case. Anyway, the importance of modelling the very early afterglow of GRBs can be applied to that of XRFs as well.

In this Letter, the possible pair loading during the γ/X-ray burst phase has not been taken into account. At least for the off-beam uniform jet model, during the initial γ-ray emission phase, large amount of electrons/positrons may be created. The annihilation time-scale is long and most of generated pairs can not be annihilated locally. These pairs will be heated by the RS, too (Li et al. 2003, and the references therein). Without doubt, the RS emission has been significantly softened. But, as argued by Fan, Dai & Lu (2004a), the *R*-band emission may not be. This can be easily understood: if there are k times the electrons/positrons associated with the baryons, the current $\nu_{\rm m}$ would be $\nu_{\rm m}/k^2$. On the other hand, the current $F_{\nu,\rm max}$ would be $kF_{\nu,\rm max}$. Then, in the slow cooling case, current $F_{\nu,\rm obs}$ should be $k^{2-\rm p}F_{\nu,\rm obs}$. For $p \sim 2.2$, such dependence is far from sensitive. In other models for XRFs, during the X-ray emission phase, at least in the viewed area, the possible pair-loading process is unimportant and can be ignored safely.

ACKNOWLEDGMENTS

YZF thanks Bing Zhang and Z. P. Jin for kind help. We also thank T. Lu, Z. G. Dai, X. Y. Wang and X. F. Wu for fruitful discussions. We appreciate the anonymous referee's valuable and detailed comments, which enabled us to improve the paper significantly. This work is supported by the National Natural Science Foundation (grants 10225314 and 10233010), and the National 973 Project on Fundamental Researches of China (NKBRSF G19990754).

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